



## Fracture mechanics and fatigue crack propagation

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**BKM**

## **Fatigue in High Strength Steel**

A new approach to predict crack propagation behaviour

Thomas Cornelius Hansen

**Serie R**

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**Fatigue in High Strength Steel. A new approach to predict crack propagation behaviour.**

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## II Preface

This report has been prepared as one part of the thesis required to obtain the Ph.d. degree at the Technical University of Denmark. The report is the result of a research project carried out at the Department of Structural Engineering, under the supervision of Prof.dr.techn M.P.Nielsen.

The project has been financed by Statens Teknisk Videnskabelige Forskningsråd.

This report deals with fracture mechanics of high strength steel. The main subjects are crack propagation under fatigue loading and presentation and evaluation of a newly developed theory, which is able to predict crack propagation under dynamic loading.

I would like to thank my supervisor for giving valuable inspiration and encouragement during the project.

Finally I express my gratitude to all other persons, who contributed to the completion of this report.

Lyngby, November 1996

Thomas Cornelius Hansen

# III Abstract

The main purpose of this paper is to present some tests with high strength steel. The paper is a follow-up of the work on fatigue and crack propagation [94.1]. It is the purpose to further evaluate the new theory of crack propagation by comparing it's results with test results. The advantage of the new theory is that crack propagation may be predicted on the basis of knowledge of well-known material parameters, contrary to the empirical formulas, the parameters of which must be determined by time consuming fatigue tests.

The paper is divided into four main parts:

- Fracture toughness standard tests (chapter 2)
- Fatigue tests (chapter 3)
- Prediction of crack propagation using the new theory, and comparing the theory with test results (chapter 4)

The relation between the stress intensity factor  $K_I$  and the critical stress intensity factor  $K_{IC}$  is the main issue. Tests determining  $K_{IC}$  as a function of  $K_I$  have been performed. It is shown that  $K_{IC}$  is not a constant, but clearly depends on  $K_I$ . The results are used to predict fatigue behaviour of high strength steel using the Energy Crack Propagation Formula (ECP).

## IV Resume

Hovedformålet med denne afhandling er at præsentere en forsøgsserie med højstyrke stål. Afhandlingen er en opfølgning af den tidligere afhandling 'fatigue and crack propagation' [94.1]. Det er formålet yderligere at eftervise den nyudviklede revnevækst-teori ved at sammenholde dens resultater med forsøg. Fordelen ved den nye teori er, at den er baseret på velkendte materialeparametre, ikke på empiriske konstanter udledt ved tidskrævende udmattelsesforsøg.

Afhandlingen er inddelt i fire hoveddele:

- Standardforsøg til bestemmelse af kritisk spændingsintensitets faktor (kap.2)
- Udmattelsesforsøg (kap.3)
- Beregning af revnevækst vha den ny teori og sammenligning af teori med forsøg (kap.4)

Hovedemnet i rapporten er fastlæggelse af sammenhængen mellem spændingsintensitets faktoren  $K_I$  og den kritiske spændingsintensitets faktor  $K_{IC}$ . Der er udført forsøg der bestemmer  $K_{IC}$  som funktion af  $K_I$ . Det er vist, at  $K_{IC}$  ikke er konstant, men tydeligt afhængig af  $K_I$ . Resultaterne er benyttet til at forudsige udmattelsesforløbet i højstyrkestål ved at benytte Energi Revnevækst Formlen (ECP).

# V Notations

$a$	Crack length
$a_p'$	Fracture zone length
$a_y$	Plastic zone length
$l_e$	Crack length correction
$B$	Thickness
$W$	Width, Elastic energy
$L$	Length
$H$	Height
$D$	Diameter
$N$	Number of cyclic load steps
$da/dN$	Crack growth rate
$P$	Force
$P_{min}$	Minimum force
$P_{max}$	Maximum force
$\Delta P$	Force increment under dynamic load ( $P_{max}-P_{min}$ )
$P_{cr}$	Critical force



$\sigma$	Stress
$f_u$	Ultimate stress
$f_y$	Yield stress
$f_t$	Tensile strength or true fracture strength
$K_I$	Stress intensity factor
$\Delta K_I$	Stress intensity factor increment under dynamic load ( $K_{I_{max}} - K_{I_{min}}$ )
$K_{IC}$	Critical stress intensity factor
$R$	Stress ratio ( $\sigma_{min}/\sigma_{max} = K_{I_{min}}/K_{I_{max}}$ )
$f$	Frequency
$C, m$	Empirical constants in Paris' equation
$c, n$	Empirical constants, Weibull size effect parameters
$M', n'$	Empirical constants, $K_{IC} - K_I$ relation

# Chapter 1

## Introduction

The purpose of this report is to present some test results on fatigue of high strength steel. Fatigue crack propagation is a well-known phenomenon. Normally it is studied by using empirical formulas. However at the Department of Structural Engineering, Technical University of Denmark, an energy balance crack growth formula has recently been developed [90.1]. This formula can be used to predict crack propagation arising both from static load and from fatigue loading.

The formula has been evaluated in the case of fatigue loading by the author in an earlier report [94.1]. An important assumption is that fatigue crack propagation depends upon a varying critical stress intensity factor  $K_{IC}$ . Normally it is assumed that  $K_{IC}$  is a constant material parameter. In the earlier work [94.1] it was shown that  $K_{IC}$  definitely is not constant, but varies with the value of the stress intensity factor  $K_I$  during crack propagation.

In this report the relation between the stress intensity factor  $K_I$  and the critical stress intensity factor  $K_{IC}$  will be analysed in detail by further test results and calculations. This report can be considered as a follow-up of the earlier work done by the author [94.1].

In this report tests with a Swedish high strength steel, Hardox 400 ( see appendix A), is presented. Firstly some fracture toughness standard tests are presented. The purpose of these tests is to determine the relation between the actual value of  $K_I$  under which the crack is initiated and the critical value  $K_{IC}$ . Secondly some fatigue crack propagation tests will be presented. The relation between  $K_I$  and  $K_{IC}$  will be used in some crack propagation calculations to predict the fatigue crack growth behaviour and the results will be compared with the results from the fatigue tests.

# Chapter 2

## Fracture toughness standard tests

### 2.1 Introduction

In this chapter the critical stress intensity factor standard test will be described and the test results presented. The purpose of these tests primarily is to determine the critical stress intensity factor  $K_{IC}$  and secondly to determine the relation between the actual value of  $K_I$  under which the crack is initiated and the final value of  $K_{IC}$ , as the final value depends upon the value of  $K_I$  during initiation.

(mm)	B	W	a	H	D
HA400	30	80	40	100	24.5

Table 2.1 *Dimensions of the  $K_{IC}$  standard test specimens*

A number of 30 specimens were tested for Hardox 400 steel with the dimensions shown in table 2.1. The crack length **a** was initiated a little longer than shown in the table, which will be commented upon, when treating the test results. Furthermore 10 tests were performed on specimens with the dimensions shown in table 2.2. These tests were made to examine the thickness effect. The specimens are numbered with two digits. All the tests with small B (B=20) have a number which starts with the digit 4. The number of the tests with large B (B=30) starts with the digits 1,2 or 3.

(mm)	B	W	a	H	D
HA400	20	47.5	22.5	60	12.5

Table 2.2 *Dimensions of the  $K_{IC}$  standard test specimens*

## 2.2 Test results

The  $K_{IC}$  standard tests were performed in a hydraulic 170 kN dynamic and static load machine. The test equipment and the test procedure are described in detail in [94.1].

In the following, two P-COD (Load - Crack opening displacement) curves will be presented as illustrative examples, one representing the large specimens ( $B=30$  mm) and one for the small specimens ( $B=20$  mm).

The P-COD curves for Hardox 400 with  $B=30$  mm showed very brittle fracture behaviour, and when the critical force  $P_{cr}$  was reached, it was not possible to measure any continuation of the curve. Therefore in this case  $P_{cr}$  was determined as the maximum load instead of using the E24 method (see [94.1]). In figure 2.1 a typical P-COD curve for Hardox 400 ( $B=30$  mm) is shown.

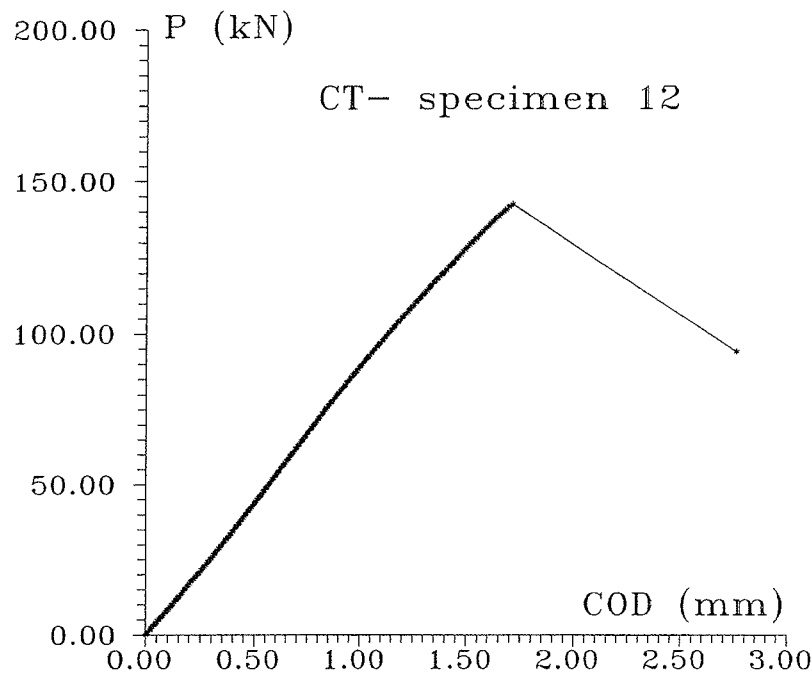


Figure 2.1 *P-COD curve for Hardox 400 ( $B=30$  mm)*



In figure 2.2 a typical P-COD curve for Hardox 400 ( $B=20$  mm) is shown. The curve follows the general type III curve (see [94.1]). The curve shows quite brittle behaviour and it was decided to determine the critical load as the maximum load to get similarity with the specimens  $B=30$  mm.

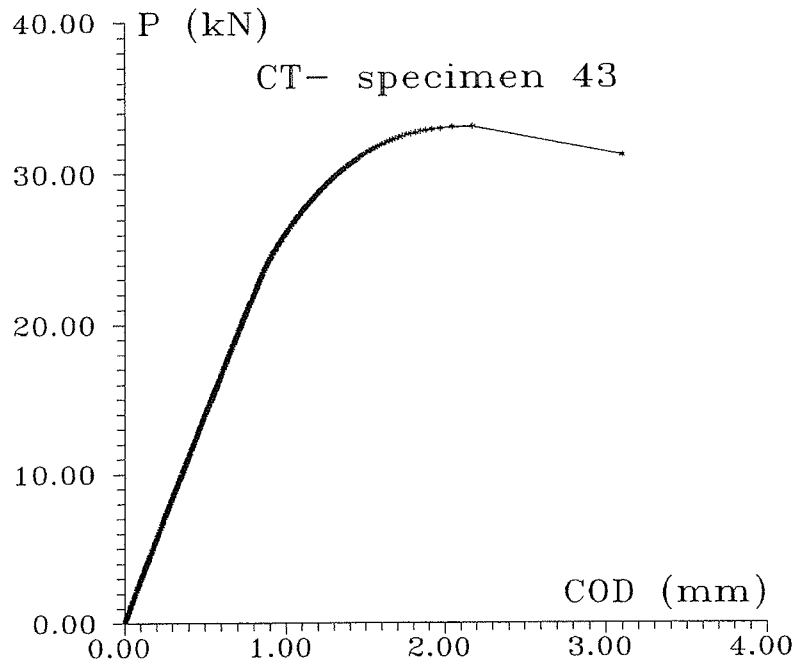


Figure 2.2 P-COD curve for Hardox 400 ( $B=20$  mm)

The value of  $P_{cr}$  for all the tests is listed in appendix C, together with the crack length  $a$ . The crack length  $a$  is measured after fracture, using the fact that the appearance of the fracture surface is very smooth in the area that has been cracked under cyclic loading and very rough in the area that has been fractured under static load. The crack length is measured as the length from the load application point to the transition point between the dynamic fracture area and the static fracture area. Figure 2.3 shows a broken CT-specimen. One might distinguish the two types of fracture areas.

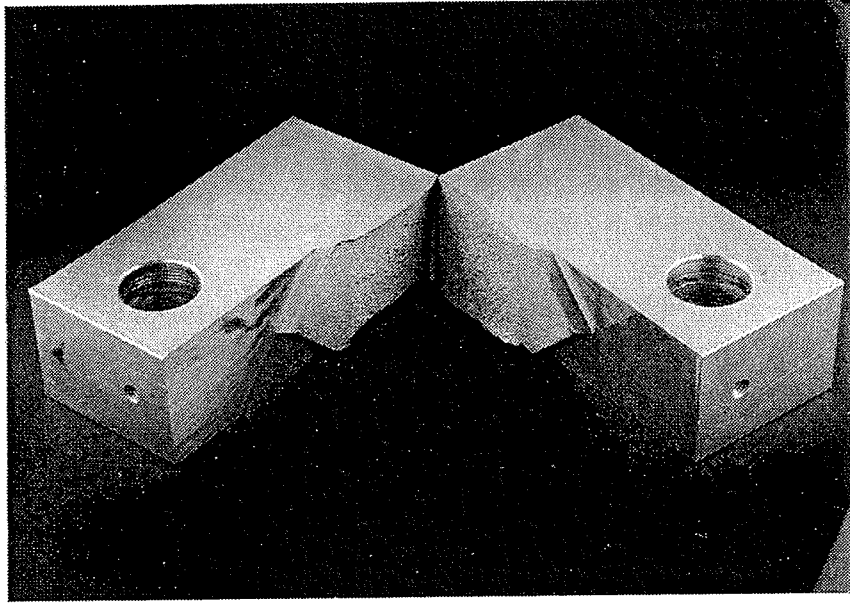


Figure 2.3 *Cracked CT-Specimen, showing the two typical fracture areas.*

The value of the crack length  $a$  is used to determine the critical stress intensity factor  $K_{IC}$  and the value of  $K_I$  under crack initiation. The stress intensity factor is determined by the formula, [86.1]:

$$K_I = \frac{P}{B \cdot W^{1/2}} \cdot \left( 29.6 \left( \frac{a}{W} \right)^{1/2} - 185.5 \left( \frac{a}{W} \right)^{3/2} + 655.7 \left( \frac{a}{W} \right)^{5/2} - 1017 \left( \frac{a}{W} \right)^{7/2} + 638.9 \left( \frac{a}{W} \right)^{9/2} \right) \quad (2.1)$$

In this formulas  $\Delta P = P_{\max} - P_{\min}$  is inserted instead of  $P$  when determining  $\Delta K_I$  and  $P = P_{cr}$  is inserted to determine  $K_{IC}$ . The minimum force is kept on a small value close to zero meaning  $\Delta P \approx P_{\max}$ .

The measured values of  $a, \Delta P$  and  $P_{cr}$  and the calculated values of  $K_I$  and  $K_{IC}$  respectively are listed in appendix C.

## 2.3 Relation between $K_I$ and $K_{IC}$

As described in section 2.1, the purpose of these tests was to examine the relation between  $K_I$  and  $K_{IC}$ . In the following figure  $K_{IC}$  is shown as a function of  $K_I$ . In all the figures a 45 degree line is inserted. The value of  $K_{IC}$  should be above this line, unless the value of  $K_I$  has reached the critical value. In all tests it has been ensured that  $K_I < K_{IC}$ .

In the earlier work [94.1] it was shown that  $K_{IC}$  was increasing with increasing  $K_I$ . In figure 2.4 all the test results are shown including the results of the earlier work, the results from the large specimens ( $B=30$  mm) and the results from the small specimens ( $B=20$  mm). We observe that the results from [94.1] are reproduced although there is a large scatter. We furthermore observe pronounced increase in  $K_{IC}$  for increasing  $K_I$ , as expected. The test specimens with the small thickness ( $B=20$ mm) gave similar results. We may therefore conclude that we have plane strain conditions where  $K_{IC}$  is independent of the thickness.

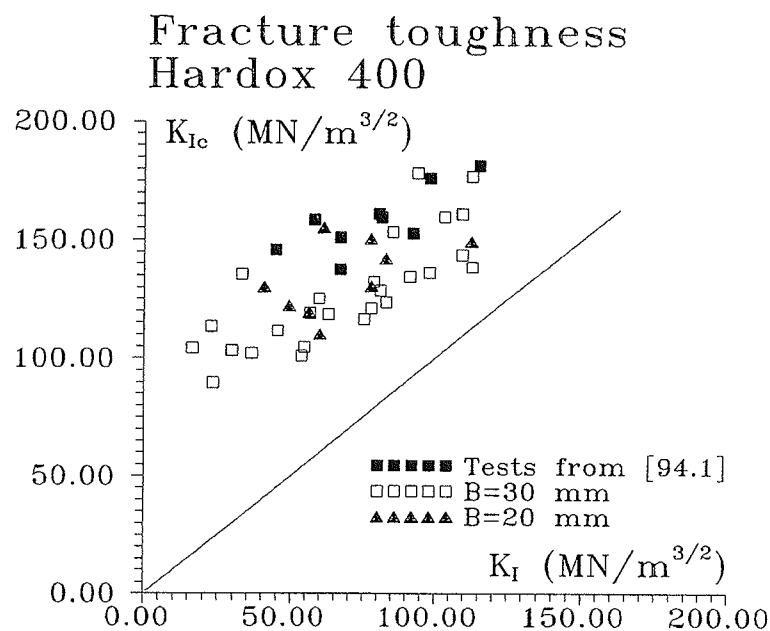


Figure 2.4

The fact that  $K_{IC}$  increases for increasing  $K_I$  has been observed in earlier tests, see for instance [70.1 p.52]. It is likely to assume, that the structure of the material in the plastic zone developed in front of the crack tip under cyclic loading is depending upon the value  $K_I$  under crack initiation. One may for instance imagine that in the plastic zone, which is subjected to very large stresses, hardening of the material takes place. The hardening thus is a function of  $K_I$ .

Changes in the structure of the material due to the hardening will influence the critical stress intensity factor  $K_{IC}$ . It is therefore natural to assume that the critical stress intensity factor, which indeed depends on the fracture zone structure, must depend on  $K_I$ .

A variation of the crack length does not affect the results as can be seen from figure 2.5, where  $K_{IC}$  is shown as function of the crack length. It may therefore be concluded that the critical stress intensity factor  $K_{IC}$  depends on the actual stress intensity factor  $K_I$  during fatigue loading.

The results will be treated in more detail in chapter 4.

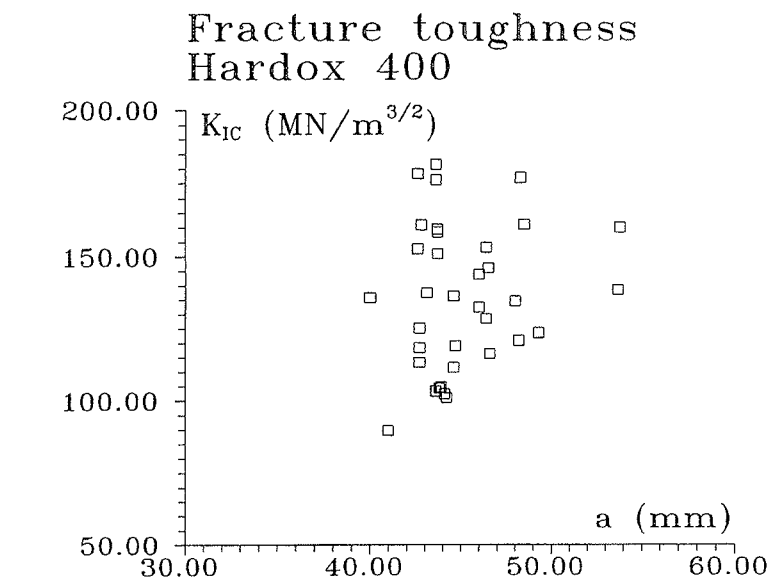


Figure 2.5  $K_{IC}$  as a function of the crack length



# Chapter 3

## Fatigue tests

### 3.1 Introduction

In this chapter the fatigue tests will be described and the test results presented. The purpose of the tests is to measure the crack propagation in the test specimens loaded by a dynamic load, and to determine the relation between the change in crack length per cycle  $da/dN$  and the stress intensity factor  $K_I$ . The crack length is measured with a Digital Image Processing System.

The fatigue tests were performed on the Swedish high strength steel Hardox 400 (see appendix B).

In the earlier work [94.1] it was found that the crack propagation velocity  $da/dN$  was very high.

The Paris  $m$  - value was measured to about  $m = 7$ , (steel normally obtains  $m=3$ ).

In the earlier work the specimens tested were very thin ( $B=2$  mm).

The manufacturing of these very thin plates might have effected the material in a way which caused the very high crack propagation rate.

To examine this two different specimens were tested. The dimensions of both specimens were the same as the specimens used in the earlier project [94.1].

One specimen type was manufactured under exactly the same conditions as before in order to reproduce the original results.

The other specimen type was cold treated during the manufacturing. All specimens were

prepared from a 4 mm thick Hardox 400 plate. First the specimens were grinded down to the thickness 2 mm.

Hereafter the specimens were polished on each side to ensure very low roughness.

A number of 5 specimens were produced of each type. The test specimens used in the fatigue tests are shown in figure 3.1.

They are of the type called the Center Crack Test specimen (CCT).

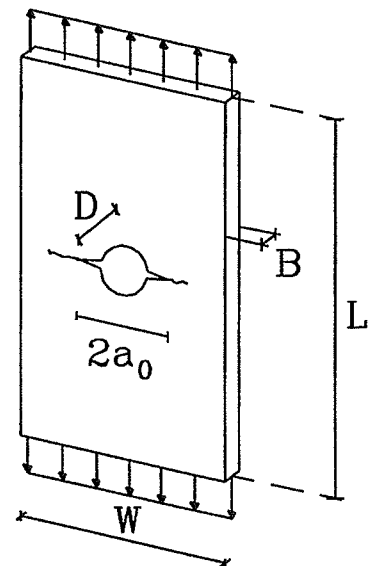


Figure 3.1 Center Crack Test specimen (CCT)

The dimensions of the tests specimens are shown in table 3.1.

[mm]	$a_0$	D	B	W	L
Hardox 400	8	8	2	80	180

Table 3.1 *Dimensions of the CCT specimens*

The specimens are numbered with two digits, xx, the first one indicates the thickness, 2 for B=2 mm, the second one indicates the test specimen number. For instance 23 is test specimen 3 with a thickness of B=2 mm. Furthermore the specimens which are cold treated during manufacturing are marked with a capital C, for instance C27.

## 3.2 Test results

In this section the test results from the fatigue tests will be presented. Test equipment and test procedure is described in detail in [94.1].

The values of the load increment  $\Delta P$  and the frequency  $f$  used in the fatigue tests are shown in table 3.2.

Hardox 400	$P_{min}$ [N]	$P_{max}$ [N]	$\Delta P = P_{max} - P_{min}$ [N]	$f$ [Hz]
B=2 mm	2500	37500	35000	22.8

Table 3.2 *Load and frequency in the fatigue tests*

In the fatigue tests the crack length  $a$  and the number of cycles  $N$  are measured. Using these results the crack velocity  $da/dN$  may be determined by the relation:

$$\frac{da}{dN} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \quad (3.1)$$

The value of  $a_i$  is chosen by the condition that for each calculated  $da/dN$ -value  $a_{i+1} - a_i > 1\text{mm}$ . This is done to ensure that at least 3 to 4 measured points are influencing the calculation of  $da/dN$  in order to minimize the uncertainty. The critical

crack length is about 25 mm, and about 30 crack lengths have been measured in each test.

The test data are given in appendix D, and they are presented graphically in this section. The crack growth is shown in figure 3.2. A total of 4 specimens (not cold treated) and 4 test specimens (cold treated) were tested successfully.

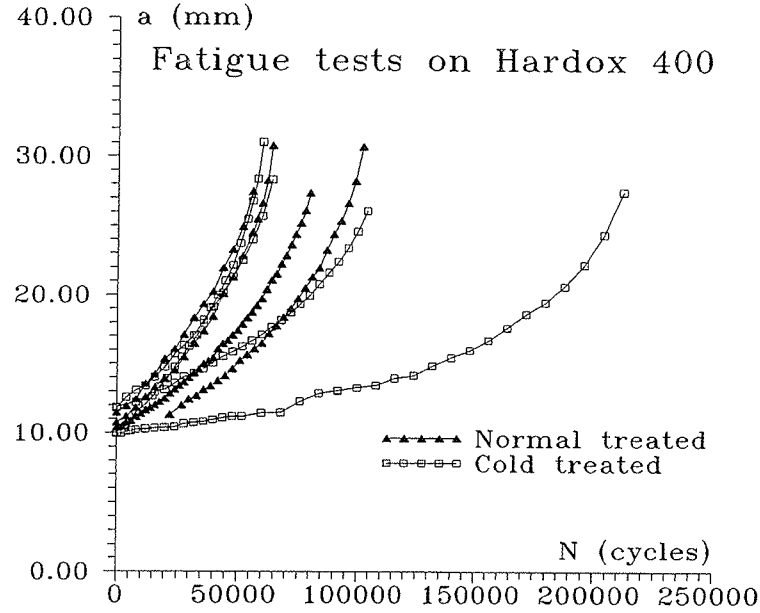


Figure 3.2 Crack propagation versus number of cycles

To calculate the crack velocity  $da/dN$  as a function of the stress intensity factor  $K_I$ ,  $K_I$  is determined by the equation, [86.1]:

$$K_I = \beta \sigma \sqrt{\pi a} \sqrt{\sec\left(\frac{\pi a}{W}\right)} \quad (3.2)$$

Here  $\beta$  is a geometrical correction parameter due to the hole at the crack in the specimen, see figure 3.1. The parameter  $\beta$  is given by the equation, [75.1]:

$$\beta = \left( 0.94 + \frac{0.34}{0.14 + \frac{a-D/2}{D}} \right) \quad (3.3)$$

The calculated  $da/dN$ -curves for all the tests are presented in figure 3.3. It was observed during the tests that among the cold treated test specimens two of the specimens (C22 and C27) had a very long initiation time  $N_i \approx 120000$  cycles before initiation of the crack. The two other cold treated specimens had an initiation time in the same range as the normal treated test specimen with  $20000 < N_i < 45000$  cycles.

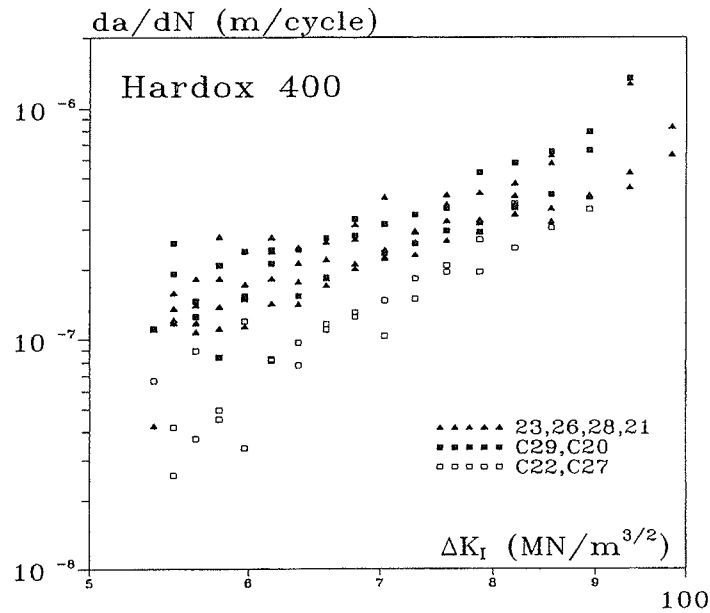


Figure 3.3 Crack Propagation rate,  $da/dN$ -curve

It is the same specimens (C22 and C27) which appear with a steeper slope and a low crack propagation rate in the  $da/dN$ -curve, figure 3.3. The purpose of the cold treated specimen was to reproduce the results from the earlier work [94.1]. It was not possible to reproduce these results. It must be concluded that the resistance of steel to fatigue is affected by the manufacturing procedure. However it seems that only two specimens were effected by the cold treatment. In the following the other two and the normal specimens will be considered as reliable results due to the fact



that they obtain a Paris  $m$  value equal to about  $m \approx 3.09$  as shown in figure 3.4, which is close to  $m = 3$  as normally expected for steel.

The Paris equation  $da/dN = C \Delta K_I^m$ , where in this case  $\Delta K_I \approx K_{I_{max}}$ , is used to give an estimate of the relation between  $da/dN$  and  $K_I$ . The parameters  $C$  and  $m$  are calculated as an average for each test and the results are shown in the figure 3.4. These values will be used in the following chapter to make a first estimate of the parameters in the crack propagation formula.

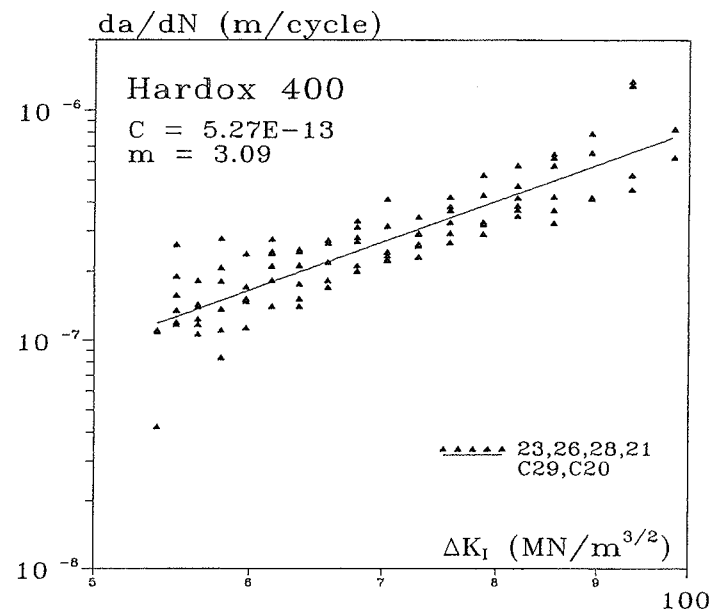


Figure 3.4 Crack Propagation rate,  $da/dN$ -curve

# Chapter 4

## Discussion of test results

In this chapter the test results presented in the previous chapters will be compared with the new theory, the Crack Propagation Formula (ECP), see formula (4.1).

$$\frac{da}{dP} = \frac{K_{I(a+1_e)}^2 \frac{\partial}{\partial P} \left( \frac{K_I^2}{2\pi f_y f_t} \right)}{K_{IC}^2 - K_{I(a+1_e)}^2} \quad (4.1)$$

The purpose is to follow-up upon the results presented in the earlier work [94.1]. Some parameters used in the formula will be taken from that work, other parameters will be determined in the following.

Firstly the relation between  $K_I$  and  $K_{IC}$  will be determined and used to determine  $K_{IC}$  in the formula (4.1). Secondly the ultimate stresses will be determined, mainly on the basis of the Weibull size effect law (weakest link theory) and some considerations on the atomic strength of materials.

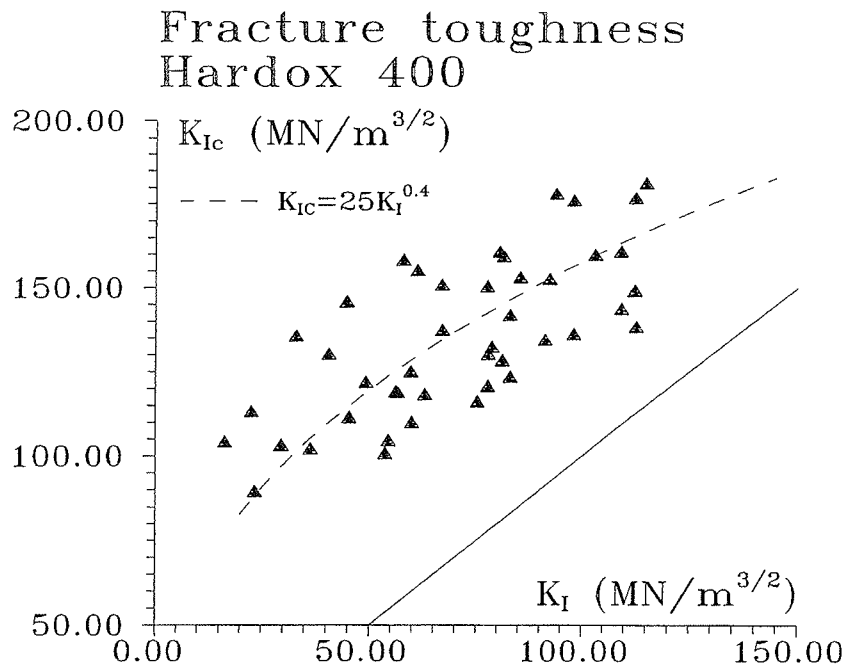
It is assumed that the  $K_I$ - $K_{IC}$ -relation in general can be described by the equation (4.2), see [90.1]:

$$K_{IC} = M' K_I^{n'} \quad (4.2)$$

In the earlier work [94.1] the relation between  $K_I$  and  $K_{IC}$  was determined on the basis of very few tests results. In this paper several tests have been performed to verify the relation and to determine it more accurately. It was assumed in the earlier work that in the low range of  $K_I$ ,  $K_{IC}$  was decreasing with increasing  $K_I$ . The present work shows that  $K_{IC}$  is increasing in the whole range of  $K_I$ , see chapter 2. This is also in agreement with the test results from the fatigue tests presented in chapter 3, where a best fit using the least square method gave the Paris m-value equal to  $m=3.09$ , see figure 3.4. This relates to a  $n'$ -value of about  $n' \approx 0.5$ , see formula (4.3), which leads to increasing  $K_{IC}$  for increasing  $K_I$  according to formula (4.2).

$$\begin{aligned} m &= 4 - 2 \cdot n' \text{ or} \\ n' &= 2 - m/2 \end{aligned} \quad (4.3)$$

There is a large scatter in the results of the  $K_{IC}$  tests, see figure 4.1. It is quite complicated to make an optimization using the least square method, due to the fact that both  $K_I$  and  $K_{IC}$  are measured with a rather large uncertainty. A value of  $n'$  in the range  $0.5 > n' > 0.3$  gives a reasonably good fit within the scatter band of the tests results. For  $n' = 0.4$  and  $M' = 25$ , which is approximately the same value as that used in the earlier work [94.1] in the range where  $K_I$  is increasing. We observe that we get a good estimate of the  $K_I - K_{IC}$  relation, see figure 4.1. These values will be used in the following calculations.



As mentioned, it was not possible to measure a decrease in  $K_{IC}$  for increasing  $K_I$  for small values of  $K_I$ , as proposed by Davidson and Lankford [83.1], ( see also [94.1]). The reason might be that the crack propagation rate measured in the tests series in [94.1] was effected by the special treatment of the material used in manufacturing the specimens, which might have led to a mixed mode I and II fracture

in the tests specimens. It may be concluded that  $K_{IC}$  is an increasing function of the stress intensity factor  $K_I$  in the whole  $K_I$ -range.

In the following the ultimate strength of the material will be determined. The ultimate strength is highly dependent on size effects due to the very small plastic zone in front of the crack tip which leads to a higher strength in the plastic zone than that measured in laboratory tests. The phenomenon is described in detail in the earlier work by the author [94.1], and will only be summarized here.

The size effect is modelled using Weibull's size effect law, [39.1] and [39.2], together with some information on the atomic strength of the material. Weibull's size effect law can be written:

$$f_u = c V^{-\frac{1}{n}} \quad (4.4)$$

where the empirical parameters  $n$  and  $c$  can be determined on the basis of the atomic strength and laboratory strength by the following formulas, see [94.1]:

$$n = \frac{19.8}{\log\left(\frac{f_u^{\text{atomic}}}{f_u^{\text{laboratory}}}\right)} \quad (4.5)$$

$$c = f_u^{\text{laboratory}} L_0^{\frac{3}{n}}$$

Here  $f_u$  is the ultimate strength, i.e. the yield strength  $f_y$  and the fracture strength  $f_t$  respectively and  $L_0$  is the size of a laboratory test specimen which in [94.1] was set to  $8 \cdot 10^{-3}$  m when determining the yield strength and  $L_0 = 5 \cdot 10^{-3}$  m due to the necked area, when determining the fracture strength  $f_t$ .

The atomic strength for steel related to the fracture strength is, see [94.1]:

$$f_t^{\text{atomic}} = 32000 \text{ MPa} \quad (4.6)$$



The atomic yield strength may be put equal to:

$$f_y^{\text{atomic}} = 8300\text{MPa} \quad (4.7)$$

The laboratory strength for the material Hardox 400 was in [94.1] found to be:

$$\begin{aligned} f_y^{\text{laboratory}} &= 1230\text{MPa} \\ f_t^{\text{laboratory}} &= 1730\text{MPa} \end{aligned}$$

The laboratory fracture strength  $f_t^{\text{laboratory}}$  has to be increased with about 20% due to the fact that in a test we often get a combination of sliding failure along the edge and a separation failure in the necked area. The cleavage strength therefore will be higher than the average stress measured over the necked area leading to, see [94.1]:

$$f_t = 1.2 f_{\text{true fracture strength}} \quad (4.9)$$

When dealing with the yield strength, it is important to bear in mind that in plane strain the yield strength exceeds considerably the uniaxial yield strength. If the linear elastic stress distribution around a sharp crack is taken as the basis, the yield strength in plane strain is found to be 3 times the uniaxial yield strength [86.1,p 115]. Irwin suggested to use a factor of 1.68,[60.2]. In [90.1] the factor used was 2.4, a value which has been found on the basis of finite element calculations. Since this is probably the best estimate, we will use it here, i.e.,

$$f_{y\text{plane strain}} = 2.4 f_{y\text{uniaxial}} \quad (4.10)$$

This factor does not affect the determination of the Weibull parameter  $n$ , because  $n$  is determined on the basis of the actual uniaxial strength, but it does affect the determination of  $c$  which describes the actual stress condition in the case given. When the yield strength at the crack tip is found to be higher than the tensile strength at the crack tip, the yield strength must of course be put equal to the tensile strength.

According to formula (4.5) we get the following Weibull parameters for the fracture strength:

$$n = \frac{19.8}{\log\left(\frac{32000}{1.2 \cdot 1730}\right)} = \underline{16.7} \quad (4.11)$$

$$c = 1.2 \cdot 1730 \cdot (5 \cdot 10^{-3})^{\frac{3}{16.7}} = \underline{801}$$

and for the yield strength:

$$n = \frac{19.8}{\log\left(\frac{8300}{2.4 \cdot 1230}\right)} = \underline{23.9} \quad (4.12)$$

$$c = 2.4 \cdot 1230 \cdot (5 \cdot 10^{-3})^{\frac{3}{23.9}} = \underline{1610}$$

In stead of using the Weibull roots  $n$  for the volume scale it has been suggested in [90.1] to use the length scale roots  $n/3$ . When this is done the length of the fracture zone might be used to determine the fracture strength  $f_t$  at the crack tip and the length of the plastic zone may be used to calculate the yield stress at the crack tip, see [94.1].

From [94.1] we have the following equations for the ultimate strengths.

The formula for the yield strength is:

$$f_y = \left[ c \left( \frac{K_I^2}{2\pi} \right)^{-\frac{3}{n}} \right]^{\frac{1}{1-\frac{6}{n}}} \quad (4.13)$$

For the fracture strength we have:

$$f_t = \left[ c \left( \frac{K_I^2}{2\pi f_y} \right)^{-\frac{3}{n}} \right]^{\frac{1}{1-\frac{3}{n}}} \quad (4.14)$$

With this approach it might be found that the theoretical yield strength  $f_y$  exceeds the fracture strength  $f_t$ . In this case we may use  $f_y = f_t$  in the crack tip.

The ultimate strengths depend on  $K_I$ , because the size of the plastic and fracture zone length depends on  $K_I$ , see equation (4.13) and (4.14).  $K_I$  may be chosen as an average value in the interval in case. In our case  $K_I$  varies from about 45 MN/m<sup>3/2</sup> to 95 MN/m<sup>3/2</sup>. As an average we may put  $K_I = 70$  MN/m<sup>3/2</sup> in the calculations.

Using formulas (4.13) and (4.14) we get the ultimate strengths:

$$\begin{aligned} f_y &= 6267 \text{ MPa} \\ f_t &= 5466 \text{ MPa} \end{aligned} \quad (4.15)$$

Since  $f_t$  is found less than  $f_y$  we must use:

$$f_y = f_t = 5466 \text{ MPa} \quad (4.16)$$

In the following the parameters shown in table 4.1 will be used to predict the crack propagation behaviour of the CCT specimens:

D	$a_0$	$M'$	$n'$	$f_t$
8 mm	8 mm	25	0.4	5466 MPa

Table 4.1 *Parameters for Center Cracked Test specimen.*

In the table  $a_0$  is half the initial crack length and D the diameter of the hole at the crack center, see figure 3.1.

In figure 4.2 the test results are compared with the Energy Crack Propagation Formula (ECP). It is observed that the theory predicts much higher crack growth rate than found in the tests.

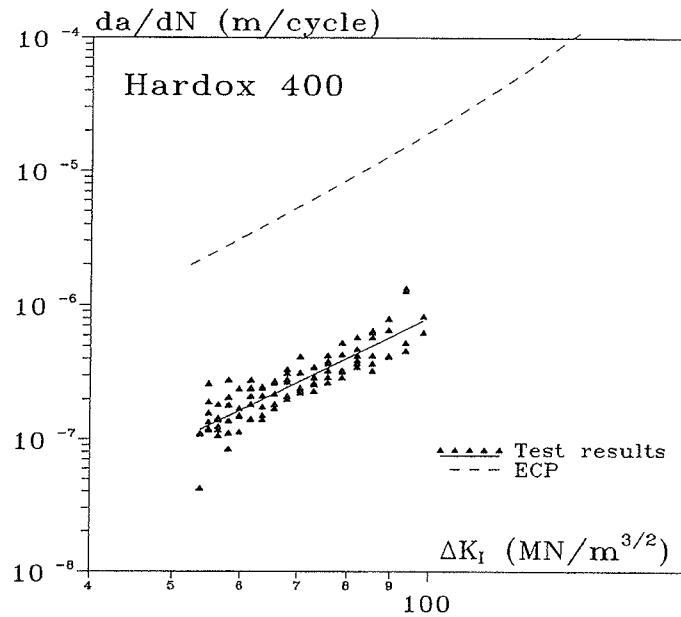


Figure 4.2 Theory compared with test results.

To examine the possible reasons for this discrepancy we begin by studying the effect of small changes in the parameters used. Firstly the relation between  $K_{IC}$  and  $K_I$  is studied. We may, within the range of the test data, choose extreme values of  $n'$  and  $M'$  as those given in table 4.2, where  $M'$  has been determined using the average value  $\Delta K_I \approx 70 \text{ MN/m}^{3/2}$ , i.e.

$$M' = 25 \cdot 70^{0.4-n'} \quad (4.17)$$

$n'$	$M'$	$f_t \approx f_y$
0.4	25	5466
0.2	58	5466
0.6	11	5466

Table 4.2 Parameters used to determine the  $K_{IC}$ - $K_I$  relation.

These values leads to the extreme  $K_{IC}$ - $K_I$  relations shown in figure 4.3.

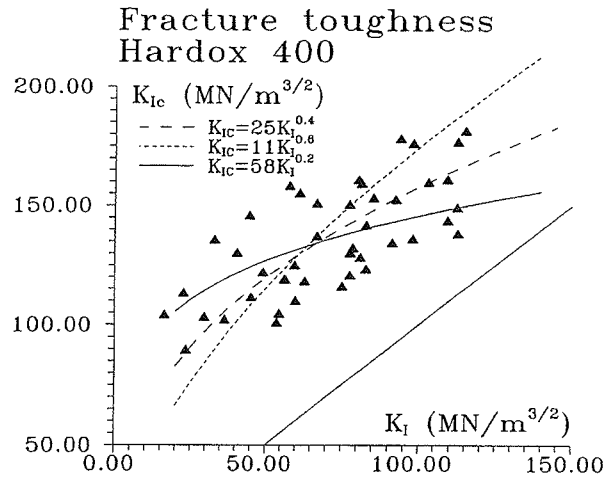


Figure 4.3 Relation between  $K_{IC}$  and  $K_I$  for different value of  $n'$ .

In figure 4.4 the extreme values of  $n'$  and  $M'$  have been used to determine the crack propagation behaviour.

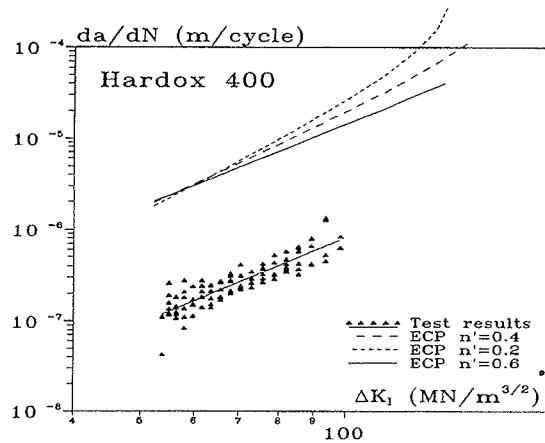


Figure 4.4 Theory compared with test results.

We observe that this does not influence the results very much.

If  $n'$  and  $M'$  are estimated on the basis of the Paris  $m$ -value and the  $K_{IC}$ -values from the fatigue test, using the values:

$$m \approx 3.06 \quad \text{and} \quad 120 \text{ MN/m}^{3/2} < K_{IC} < 150 \text{ MN/m}^{3/2}$$

we get:

$$\begin{aligned}
n' &= 2 - 0.5m = 0.45 \\
M' &= \frac{120}{120^{0.6}} = 7 \\
M' &= \frac{150}{150^{0.2}} = 55
\end{aligned}
\tag{4.18}$$

Since  $M'$  must be lying somewhere in between 55 and 7, we may conclude that our choice  $M' = 25$  and  $n' = 0.4$  may be considered reasonable, and that a change within a reasonable range does not affect the results very much.

The influence from the ultimate strengths will now be examined. In figure 4.5 calculations with ECP using the ultimate strengths  $f_u = f_t \approx f_y \approx 10000$  MPa and 20000 MPa respectively are shown.

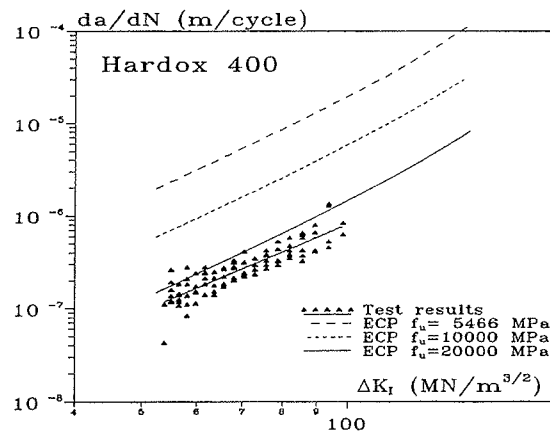


Figure 4.5 *Theory compared with test results.*

It is observed that putting the ultimate strengths equal to 20000 MPa the theory does predict the crack propagation behaviour well. An increase of the ultimate strengths might be quite natural, because the hardening taking place in the fracture zone and in the plastic zone will of course affect not only the  $K_{IC}$ -value but also the strength values. This effect has not yet been taken into account. However a strength of 20000 MPa approaches the atomic strength and it does not seem likely that hardening may have such a pronounced effect.

We must conclude that better agreement can not in a reasonable way be obtained by changing the parameters of the model.

If we compare the fatigue test results obtained here with typical  $da/dN$  -  $\Delta K_I$  curves for other types of steel [91.1], see figure 4.6, we observe that steel with a medium strength (A470 and AISI) gives similar results as the Hardox steel and we observe that high strength steel (Commercial) gives higher crack propagation rates, although high ultimate strength should lead to lower crack propagation rate according to ECP unless the  $K_{IC}$ -value is decreased correspondingly. Normally this is the case. It is well-known that most steels have crack growth rates which lead to a rather narrow scatter band. However this pattern seems to be violated by ductile steels with low strength and by the Hardox steel treated here. For the low strength, ductile steels there will be substantial plastic deformations at the crack tip.

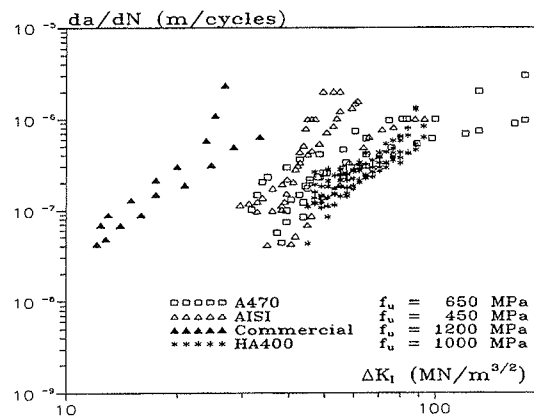


Figure 4.6 Comparison of different steel alloys.

The low crack growth rates for ductile low strength steels and maybe our Hardox steel may be explained by a phenomenon called crack closure. Crack closure has been treated by the author in [96.1] and for detailed information the reader is referred to [95.1]. In the following the effects of crack closure will be shortly summarized.

Because of the plastic deformations the crack will close during unloading before the specimen is totally unloaded. Since the crack is open only for a part of the loading sequence an effective stress intensity factor range  $\Delta K_{eff} = K_{Imax} - K_{op}$  is governing the crack growth,  $K_{op}$  being the stress intensity factor when the crack starts to open and the crack starts to propagate. This explains the delay of crack propagation caused by overloading. Furthermore the crack propagation is delayed in general and is to some degree a function of  $\Delta K_{eff}$  instead of  $\Delta K_I$ . If the R ratio,

i.e. the  $P_{\min}/P_{\max}$  ratio is high the effect will be reduced, because  $K_{\min}$  approaches  $K_{\text{op}}$  and the effective stress range  $\Delta K_{\text{eff}}$  equals  $\Delta K_I$ .

Elber [71.2] was the first to describe this phenomenon. He suggested the simple relation:

$$\Delta K_{\text{eff}} = (0.5 + 0.4R) \Delta K_I \quad (2.37)$$

where  $\Delta K_{\text{eff}}$  should be used in stead of  $\Delta K_I$  in the crack propagation formulas, like the Paris formula, i.e.

$$\frac{da}{dN} = C \Delta K_{\text{eff}}^m \quad (2.38)$$

In the tests described in this paper  $\sigma_{\min}$  is very small and we may consider  $R \approx 0$ . As a rough estimate we may use a method suggested in [96.1] valid for normal strength steel. The method take the effect of crack closure into account by using a reduced, effective stress intensity factor  $K_{\text{eff}} = K_{\text{Imax}} - K_{\text{op}}$  in the calculation, where  $K_{\text{op}}$  is determined by the crack opening stress at the crack tip,  $S_o$ , which approximately can be put equal to  $S_o \approx 0.3 \cdot \sigma_{\max}$ . In Elbers expression we have  $S_o = 0.5 \cdot \sigma_{\max}$  for  $R = 0$ . Since we do not know the exact effect of crack closure in the Hardox 400 tests, both the factor 0.3 and 0.5 has been used in the calculations shown in figure 4.7.

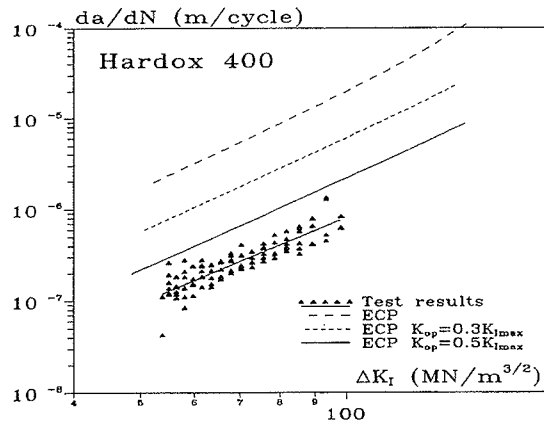


Figure 4.7 Effect of crack closure compared with test results.



We observe that crack closure may explain why the predicted crack propagation rate is too high. However much more research is needed before any final conclusion may be taken.

## Chapter 5

### Recommendations for future research

There are many subjects which should be researched more in connection with the further evaluation of the Energy Balance Crack growth formula.

The most important ones are:

1) The fracture strength and the yield strength at the crack tip.

It is possible that the cleavage strength is highly underestimated and that the yield strength is overestimated by using the Weibull size effect theory. As mentioned in [94.1] it has been found in some cases that the atomic cleavage strength is reached already at a length scale of 1  $\mu\text{m}$ . On the other hand the Weibull theory may be extended too far, when used for scaling the yield strength. The effect of hardening on the strength parameters, tensile strength and yield strength, should also be studied.

2) The influence of the microstructure of the steel.

It is likely that account must be taken of parameters like grain size, strength in the grains and along grain boundaries, influence of foreign atoms on the atomic strength, number and type of dislocations etc. These parameters of course influence the parameters already used in the equation, but it should be investigated whether other parameters could be included. For instance the order of magnitude of the crack extension in one cycle is  $10^3$  atomic distances. Thus a number of foreign atoms will be activated in one crack extension step, which could mean that the strength to be used in the crack growth formula should include the effect of foreign atoms. It is also to be expected that things will be different whether one crack extension step is within the grain size or include more grains.

3) The mechanism of crack growth.

Much work has been done in this area. In relation to the crack growth formula two extreme mechanisms should be examined further. The one, which has been tacitly assumed, is that the whole process zone is moving in the direction of the crack axis. For some materials, for instance very ductile ones, other mechanisms should be studied, for instance a mechanism where the yield zone is unchanged in a number of crack extension steps and failure is by local crack development in the yield zone.

4) The effective crack length.

It must be admitted that the determination of the effective crack length has been done by very rough methods. More refined methods should be introduced and used to evaluate the present way of calculating the effective crack length.

5) The effect of crack closure.

In this paper it has been suggested that by including crack closure better agreement might be obtained for low and medium strength steels. If the basic ideas of the model can be maintained, the effect of crack closure should be taken into account along the lines mentioned searching for improved values of the crack opening stress intensity factor.

# Chapter 6

## Conclusion

This paper is a follow-up on the work [94.1]. The main purpose has been to further evaluate the basic concepts of the Energy Crack Propagation Formula (ECP), and to examine the capability of ECP to predict crack propagation behaviour.

As a main conclusion it has been verified that the critical stress intensity factor  $K_{IC}$  varies with the stress intensity level. It has been shown that this dependency may be used to calculate the slope of the  $da/dN-\Delta K_I$  curve, which means that it is possible to calculate the Paris  $m$  value.

The level of crack propagation rate is highly dependent on the ultimate strength and the critical stress intensity factor  $K_{IC}$ . It has been shown, that for the steel tested, ECP can not estimate the level of the crack propagation rate in its present form. Several parameters influence the fracture mechanical parameters, such as microstructure, size effects, hardening of the material etc. It is necessary to perform further research in these areas in order to understand the effect on the fracture mechanical parameters.

The effect of crack closure has been investigated. It was shown that to some extent this may explain the delay in fatigue crack growth, but much more research is needed in this field before any final conclusion may be drawn.

The Energy Crack Propagation formula (ECP) has been shown to be able to predict crack propagation in different metals in this and the earlier work, when the correct fracture mechanical parameters are used. Therefore the model can be recommended for future research to understand the mechanisms of fatigue and crack propagation. Even more research is needed before it can be used for practical applications.

# Appendix A

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# Appendix B

## Material descriptions

### High strength steel Hardox 400

**Producer** Swedish Steel Oxelösund  
Box 1000  
61301 Oxelösund  
Sweden

**Usage** Hard wearing steel. Used in trucks, bulldozers, wheel constructions and much more.

<b>Composition</b>	C	Si	Mn	P	S	Cr	Mo	B
(in %)	0.20	0.10-0.70	1.70	0.025	0.01	0.80	0.80	0.005

The remainder is steel, the steel is fine grain treated.  
The values are maximum values.

<b>Strength</b>	Yield strength	Ultimate strength	Elongation
Factory	1000 MPa	1250 MPa	10 %
Values			

## Appendix C

### Data from the $K_{IC}$ standard tests

In this appendix all the test results from the  $K_{IC}$  standard tests are presented. The data include the crack length  $a$  initiated under a dynamic load  $\Delta P = P_{\max} - P_{\min}$ , the critical load  $P_{cr}$ , and finally the calculated  $K_I$  and  $\Delta K_I$  value under initiation and the critical  $K_{IC}$  value at fracture. The following expression [86.1] has been used:

$$K_I = \frac{P}{B \cdot W^{1/2}} \left( 29.6 \left( \frac{a}{W} \right)^{1/2} - 185.5 \left( \frac{a}{W} \right)^{3/2} + 655.7 \left( \frac{a}{W} \right)^{5/2} - 1017 \left( \frac{a}{W} \right)^{7/2} + 638.9 \left( \frac{a}{W} \right)^{9/2} \right)$$

Regarding notation, see section 2.1.  $K_{IC}$  is calculated using  $P_{cr}$  and  $a$ , while  $\Delta K_I$  is calculated using  $\Delta P$  and  $a$ .

(mm)	B	W
small HA400	20	47.5
large HA400	30	80

Some of the tests are not valid due to the reasons listed below.

- 1) Test 41 was loaded dynamically. At the end of the dynamic test the test machine could not keep the loading level which led to smaller load than expected. The results can't be considered as reliable and are not used in the report.

Units:

[a]=mm; [P]=kN; [ $K_I$ ]=MN/m<sup>3/2</sup>

large Ha400	$a_0$	$P_{max}$	$\Delta P$	$P_{cr}$	$K_I$	$\Delta K_I$	$K_{Ic}$
10	48.5	66.8	60	98.3	109.33	98.2	160.9
11	46.0	75.4	71.3	99.2	109.35	103.4	143.8
12	42.6	75.0	71.4	142.3	93.91	89.4	178.2
13	42.7	50.1	45.7	94.2	63.04	57.5	118.4
14	41.0	20.0	13.2	76.3	23.48	15.5	89.7
15	43.6	22.8	16.8	79.1	29.59	21.8	103.2
16	44.1	27.3	20.6	76.7	36.44	27.5	102.2
17	42.7	18.1	13.5	90.1	22.66	16.9	113.3
18	40.0	29.2	22.9	119.9	33.03	25.9	135.7
19	44.6	33.3	26.9	81.9	45.31	36.6	111.5



large HA400	$a_0$	$P_{\max}$	$\Delta P$	$P_{cr}$	$K_I$	$\Delta K_I$	$K_{Ic}$
20	43.8	12.5	8.34	79.2	16.44	10.97	104.2
21	44.2	40.9	35.9	75.4	53.66	47.1	100.9
22	42.7	47.5	41.9	99.5	59.74	52.7	125.1
23	43.9	42	37.4	79.2	55.48	49.4	104.7
24	44.7	41.4	35.7	86.9	56.59	48.8	118.9
25	53.8	46.9	38.6	72.7	103.16	84.9	159.9
26	48.2	48.3	43.2	74.5	77.82	69.6	120.8
27	49.3	48.7	42.4	72.5	83.04	72.3	123.6
28	46.4	54.9	48.9	86.9	81.06	72.2	128.4
29	53.7	51.6	43.4	63.3	112.83	94.9	138.4

large HA400	$a_0$	$P_{\max}$	$\Delta P$	$P_{cr}$	$K_I$	$\Delta K_I$	$K_{Ic}$
30	46.4	57.8	51.7	103.7	85.41	76.4	153.2
31	48	57.2	51.7	84.3	91.28	82.5	134.5
32	46	54.2	49	91.3	78.65	71.1	132.4
33	44.6	72	66	100	98.07	89.9	136.2
34	48.3	69.5	63.2	109.4	112.61	102.4	176.9
35	46.6	50.5	45.1	77.9	75.25	67.2	116.2

small HA400	$a_0$	$P_{\max}$	$\Delta P$	$P_{cr}$	$K_I$	$\Delta K_I$	$K_{Ic}$
40	32.9	16.4	14.4	31.8	77.67	68.2	150.5
41 <sup>1</sup>	36.7	17.1	15.3	16.3	125.62	112.4	119.4
42	30.8	20.4	16	34.1	77.90	61.1	130.3
43	32.5	24.8	19.4	32.9	112.49	88	149.3
44	30.4	11.1	8.2	35.4	40.61	30	130.2
45	33.9	9.4	5.1	23.1	49.21	26.7	121.9
46	34.2	15.2	10.9	26	82.97	59.5	142
47	32.5	13.5	10.3	34.2	61.21	46.7	155.2
48	32.5	12.4	7.9	26.3	56.19	35.8	119.3
49	37	7.9	3.44	14.5	59.94	26.1	110.1

note 1: The test is not valid.

# Appendix D

## Data from the fatigue tests

In this appendix all the test results from the fatigue tests are presented, i.e. the measured crack length  $a$  as function of number of cycles  $N$ .

All test specimens were loaded dynamically with  $\Delta P = 37500 - 2500 \text{ N} = 35000 \text{ N}$ , at the frequency  $f = 22.8 \text{ Hz}$ .

A number of 10 test specimens were manufactured of Hardox steel, specimens 20-29. 5 test specimens were cold treated in the manufacturing fase.

Two tests were not valid due to the reasons listed below.

- 1) The crack propagated asymmetrically in specimen 25 which led to unreliable results.
- 2) Specimen 24 was subjected to compression by a mistake, and the specimen failed in buckling, and could therefore not be tested in fatigue.

Test results from these tests are not used in the report.

Units:

[a]=mm; [N]=Number of cycles;

Specimen cct20; Cold treated				
Crack initiation: $N_i = 36000$ ;				
	meas/a = 10.1		meas/a = 13.2	
N	meas	a [mm]	meas	a [mm]
0	126	12.47524	147	11.13636
4000	133	13.16831	158	11.96969
8000	140	13.86138	162	12.27272
12000	143	14.15841	167	12.65151
16000	150	14.85148	174	13.18181
20000	156	15.44554	185	14.01515
24000	165	16.33663	199	15.07575
28000	172	17.0297	206	15.60606
32000	180	17.82178	215	16.28787
36000	195	19.30693	225	17.04545
40000	204	20.19801	238	18.0303
44000	215	21.28712	251	19.01515
48000	228	22.57425	265	20.07575
52000	240	23.76237	280	21.21212
56000	257	25.44554	297	22.50
60000	276	27.32673	317	24.01515
64000	310	30.69306	342	25.90909

Specimen cct21; Normal treated				
Crack initiation: $N_i = 32000$ ;				
	meas/a = 10.3		meas/a = 13.2	
N	meas	a [mm]	meas	a [mm]
0	121	11.74757	148	11.21212
4000	126	12.233	154	11.66666
8000	131	12.71844	160	12.12121
12000	143	13.88349	174	13.18181
16000	147	14.27184	187	14.16666
20000	162	15.72815	197	14.92424
24000	168	16.31067	208	15.75757
28000	182	17.6699	218	16.51515
32000	193	18.73786	237	17.95454
36000	206	20	246	18.63636
40000	215	20.87378	259	19.62121
44000	235	22.81553	278	21.0606
48000	248	24.07766	296	22.42424
52000	267	25.92233	316	23.93939
56000	300	29.12621	340	25.75757

Specimen cct22; Cold treated				
Crack initiation: $N_i = 118000$ ;				
	meas/a = 10.6		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
0	108	10.18867	127	9.694656
2000	108	10.18867	127	9.694656
4000	110	10.37735	128	9.770992
6000	110	10.37735	130	9.923664
8000	111	10.47169	131	10
12000	112	10.56603	131	10

Specimen cct22; Cold treated				
Crack initiation: $N_i = 118000$ ;				
	meas/a = 10.6		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
16000	113	10.66037	131	10
20000	113	10.66037	132	10.07633
24000	113	10.66037	134	10.229
28000	116	10.94339	136	10.38167
32000	117	11.03773	137	10.45801
36000	118	11.13207	138	10.53435
40000	120	11.32075	139	10.61068
44000	122	11.50943	140	10.68702
48000	122	11.50943	143	10.91603
52000	122	11.50943	143	10.91603
60000	127	11.98113	143	10.91603
68000	128	12.07547	143	10.91603
76000	135	12.73584	155	11.83206
84000	144	13.5849	159	12.1374
92000	147	13.86792	161	12.29007
100000	148	13.96226	165	12.59541
108000	149	14.0566	168	12.82442
116000	156	14.71698	173	13.2061
124000	157	14.81132	177	13.51145
132000	167	15.75471	183	13.96946
140000	174	16.41509	190	14.50381
148000	180	16.98113	196	14.96183
156000	189	17.83018	204	15.57251
164000	203	19.15094	211	16.10687
172000	216	20.37735	221	16.87022
180000	227	21.41509	229	17.48091
188000	241	22.73584	243	18.54961

Specimen cct22; Cold treated				
Crack initiation: $N_i = 118000$ ;				
	meas/a = 10.6		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
196000	261	24.62264	259	19.77099
204000	289	27.26415	281	21.45038
212000	332	31.32075	309	23.58778

Specimen cct23; Normal treated				
Crack initiation: $N_i = 42000$ ;				
	meas/a = 11.2		meas/a = 12.4	
N	meas	a [mm]	meas	a [mm]
0	120	10.71428	124	10
2000	121	10.80357	125	10.08065
4000	125	11.16071	128	10.32258
6000	127	11.33928	129	10.40322
8000	130	11.60714	133	10.7258
10000	133	11.875	135	10.88709
12000	136	12.14285	138	11.12903
14000	139	12.41071	139	11.20967
16000	142	12.67857	141	11.37096
18000	144	12.85714	144	11.6129
20000	148	13.21428	145	11.69354
22000	151	13.48214	151	12.17741
24000	155	13.83928	154	12.41935
26000	158	14.10714	158	12.74193
28000	160	14.28571	162	13.06451
30000	166	14.82142	163	13.14516
32000	170	15.17857	167	13.46774
34000	173	15.44642	170	13.70967
36000	179	15.98214	173	13.95161

Specimen cct23; Normal treated				
Crack initiation: $N_i = 42000$ ;				
	meas/a = 11.2		meas/a = 12.4	
N	meas	a [mm]	meas	a [mm]
38000	181	16.16071	176	14.19354
40000	182	16.25	181	14.59677
42000	192	17.14285	185	14.91935
44000	199	17.76785	187	15.08064
46000	200	17.85714	192	15.48387
48000	206	18.39285	195	15.7258
50000	210	18.75	199	16.04838
52000	215	19.19642	205	16.53225
54000	220	19.64285	211	17.01612
56000	226	20.17857	214	17.25806
58000	233	20.80357	219	17.66129
60000	239	21.33928	224	18.06451
62000	243	22.0909	230	18.69918
64000	252	22.90909	236	19.18699
66000	256	23.27272	243	19.75609
68000	266	24.18181	249	20.2439
70000	274	24.90909	255	20.7317
72000	285	25.90909	262	21.30081
74000	295	26.81818	269	21.86991
76000	307	27.90909	276	22.43902
78000	319	29	285	23.17073
80000	336	30.54545	297	24.14634



Specimen cct25; Normal treated				
Crack initiation: $N_i = 44000$ ;				
	meas/a = 10.3		meas/a = 13.3	
N	meas	a [mm]	meas	a [mm]
0	103	10	139	10.45112
4000	104	10.09708	153	11.50375
8000	105	10.19417	163	12.25563
12000	106	10.29126	164	12.33082
16000	109	10.58252	175	13.15789
20000	113	10.97087	186	13.98496
24000	120	11.65048	191	14.3609
28000	120	11.65048	197	14.81203
32000	120	11.65048	206	15.48872
36000	126	12.233	213	16.01503
40000	136	13.20388	223	16.76691
44000	138	13.39805	233	17.51879
48000	140	13.59223	243	18.27067
52000	140	13.59223	255	19.17293
56000	150	14.5631	266	20
60000	155	15.04854	281	21.12781
64000	155	15.04854	297	22.33082
68000	162	15.72815	310	23.30827
72000	165	16.01941	328	24.66165
76000	175	16.99029	348	26.16541
80000	190	18.4466	372	27.96992
84000	200	19.41747	399	30

Specimen cct26; Normal treated				
Crack initiation: $N_i = 46000$ ;				
	meas/a = 7.7		meas/a = 8.8	
N	meas	a [mm]	meas	a [mm]
0	69	8.961038	89	10.11363
2000	69	8.961038	89	10.11363
12000	71	9.220779	90	10.22727
22000	86	11.16883	101	11.47727
27000	93	12.07792	105	11.93181
30000	96	12.46753	109	12.38636
33000	98	12.72727	111	12.61363
36000	101	13.11688	115	13.06818
39000	103	13.37662	118	13.40909
42000	106	13.76623	121	13.75
45000	108	14.02597	125	14.20454
48000	113	14.67532	128	14.54545
51000	117	15.1948	134	15.22727
54000	122	15.84415	136	15.45454
57000	124	16.10389	141	16.02272
60000	127	16.4935	145	16.47727
63000	133	17.27272	150	17.04545
66000	139	18.05194	154	17.5
69000	142	18.44155	161	18.29545
72000	149	19.35064	164	18.63636
75000	153	19.87012	172	19.54545
78000	159	20.64935	179	20.3409
81000	167	21.68831	184	20.90909
84000	171	22.20779	191	21.70454
87000	180	23.37662	203	23.06818
90000	190	24.67532	212	24.0909
93000	198	25.71428	220	25

Specimen cct27; Cold treated				
Crack initiation: $N_i = 120000$ ;				
	meas/a = 10.5		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
0	131	12.47619	148	11.2977
8000	134	12.7619	153	11.67938
16000	145	13.80952	158	12.06106
20000	148	14.09523	159	12.1374
24000	154	14.66666	164	12.51908
28000	160	15.23809	169	12.90076
32000	162	15.42857	172	13.12977
36000	166	15.80952	176	13.43511
40000	172	16.38095	180	13.74045
44000	179	17.04761	183	13.96946
48000	183	17.42857	187	14.2748
52000	186	17.71428	193	14.73282
56000	192	18.28571	197	15.03816
60000	198	18.85714	201	15.34351
64000	204	19.42857	208	15.87786
68000	211	20.09523	212	16.1832
72000	218	20.7619	218	16.64122
76000	226	21.5238	224	17.09923
80000	234	22.28571	230	17.55725
84000	243	23.14285	241	18.39694
88000	254	24.19047	249	19.00763
92000	264	25.14285	257	19.61832
96000	276	26.28571	268	20.45801
100000	292	27.80952	280	21.37404
104000	313	29.80952	292	22.29007

Specimen cct28; Normal treated				
Crack initiation: $N_i = 28000$ ;				
	meas/a = 10.0		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
0	103	10.3	147	11.22137
4000	108	10.8	152	11.60305
8000	113	11.3	162	12.36641
12000	120	12	172	13.12977
16000	130	13	178	13.58778
20000	138	13.8	183	13.96946
24000	146	14.6	189	14.42748
28000	156	15.6	201	15.34351
32000	166	16.6	214	16.33587
36000	176	17.6	224	17.09923
40000	190	19	234	17.86259
44000	201	20.1	263	20.07633
48000	213	21.3	278	21.22137
52000	230	23	296	22.59541
56000	247	24.7	319	24.35114
58000	256	25.6	332	25.34351
60000	270	27	344	26.25954
62000	288	28.8	362	27.63358
64000	320	32	387	29.54198

Specimen cct29; Cold treated				
Crack initiation: $N_i = 16000$ ;				
	meas/a = 10.0		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
0	98	9.8	134	10.229
4000	100	10	143	10.91603

Specimen cct29; Cold treated				
Crack initiation: $N_i = 16000$ ;				
	meas/a = 10.0		meas/a = 13.1	
N	meas	a [mm]	meas	a [mm]
8000	114	11.4	152	11.60305
12000	118	11.8	162	12.36641
15000	123	12.3	170	12.97709
18000	130	13	179	13.66412
21000	137	13.7	186	14.19847
24000	145	14.5	197	15.03817
27000	152	15.2	207	15.80152
30000	159	15.9	217	16.56488
33000	167	16.7	228	17.40458
36000	176	17.6	240	18.32061
39000	187	18.7	254	19.38931
42000	196	19.6	267	20.38167
45000	206	20.6	281	21.45038
48000	216	21.6	297	22.67175
51000	234	23.4	315	24.0458
54000	252	25.2	337	25.72519
56000	265	26.5	354	27.0229
58000	280	28	376	28.70229
60000	310	31	407	31.0687